COMMISSIONING OF SOLEIL FAST ORBIT FEEDBACK SYSTEM

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Abstract

The SOLEIL Fast Orbit Feedback system has been integrated in the BPM electronics, using the FPGA resources of the LIBERA modules. On top of their position measurement, the FPGAs compute the orbit correction and drive the power-supplies of the 48 dedicated air coil correctors. Position data are distributed all over the ring by a dedicated network connecting the 120 BPMs modules together. The correction rate is 10 kHz and is applied with low latency. Even if at almost all the source points, the high frequency stability specifications have already been achieved thanks to great care in the design of the machine, remaining vibrations are still observed in the 46-54 Hz band and during the changes in gap and phase of some insertion devices. Those perturbations can be efficiently damped by the Fast Orbit Feedback system. While the BPM system has been operational for some time, the Fast Orbit Feedback system is presently in its commissioning phase. The design and first results of the latter are reported.

INTRODUCTION

The SOLEIL BPM system has been in operation from the start of the Storage Ring commissioning in May 2006 [1, 2]. There are 120 BPMs, 72 are located in the arcs and there is one at each end of the 24 straight sections. The electronic processing has been defined and designed by SOLEIL and Instrumentation Technologies, a company in Slovenia [3]. The BPM electronics consists of one crate per BPM called “LIBERA”. It is plugged into the 50 Hz mains and the Ethernet control network. It has been designed from the start for supporting a Fast Orbit Feedback embedded into the BPM processing FPGA. The BPM digital electronics has subsequently equipped most of the new storage rings around the world.

The stability of the beamline at the source points are required to be better than 1/10th the rms size and angular divergence of the photon beam.

Photon Source	σ_x/10 µm	σ'_x/10 µrad	σ_z/10 µm	σ'_z/10 µrad
Bending magnets (≤ 35 keV)	N/A	N/A	1.5	5.3
Hard X-ray IDs (≤ 18 keV)	39	1.5	0.55	0.51
Soft X-ray IDs (≤ 1.6 keV)	18.3	3.4	0.65	1.6
UV IDs (≤ 0.04 keV)	32	4.6	6	4.2

Table 1: Beam stability requirements at source points with ε_H = 3.75 nm.rad and K = 0.4%

These parameters for the main beamline types depend on their location on the machine and on their maximum photon energy. They are shown in table 1.

SLOW AND FAST ORBIT FEEDBACK

A Slow Orbit Feedback (SOFB) based on an SVD algorithm with the 120 BPMs and 56 correctors in each plane is operational since May 2007 [2].

Initially, the FOFB was mainly meant to suppress the residual vibrations at frequencies higher than 1 Hz; the slow drifts, below 0.01 Hz being corrected by the SOFB. The SOFB acts on 56 correctors built in the sextupoles. One of the technological innovations at SOLEIL is the extensive use of NEG coated aluminium vacuum chambers in the arcs and straight sections. It improves the vacuum pressure and beam lifetime without increasing the broadband wall impedance. However, the eddy currents in aluminium suppress the magnetic field over few Hz in the vacuum chamber.

In each plane the FOFB acts on 48 fast air correctors that are installed around stainless steel BPM bellows, at the ends of the 24 straight sections. The correctors can yield orbit kicks in the ±20 µrad range, which is much less than that of the slow correctors (±0.8 mrad in H and ±0.6 mrad in V, values necessary for the closed orbit distortion), but its cut-off frequency due to eddy currents is ≥ 2.5 kHz. The power-supplies can provide currents in the ±10A range within ±24V voltage limits.

The Slow and the Fast Orbit Feedback systems do not use the same set of correctors, which is not a problem if the two systems are kept well separated by functioning in different frequency ranges. Actually, we found that the FOFB is very efficient at suppressing two unexpected sources of orbit perturbation: i) use of the overhead cranes in the experimental hall during photon beam delivery ii) imperfections of the feedforward correction process during undulator gap changes. At the moment, the feedforward steerers correct the orbit very well before and after gap changes, but not well enough during the transitions. The cause of the problem is currently being addressed (better synchronization between the four feedforward correctors and smooth interpolation between consecutive points of the correction tables). It should be corrected by the end of the year, but in the mean time, the FOFB would greatly help.

The tests conducted so far were aimed at demonstrating that the FOFB can stabilize the beam position alone (without SOFB) for about 8 hours without saturating the air correctors.

BEAM NOISE SPECTRUM

We identify three different ranges in the beam spectrum: i) the “high frequency” noise from 1 to 150 Hz, ii) the beam movements due to crane operation and undulator gap changes in the 0.01 to 1 Hz bandwidth, and iii) the slow drifts, mainly from thermal effects, from DC to 0.01 Hz.

The high frequency noise without orbit feedback is shown in figure 1. The integrated noise amounts to 3 µm in horizontal and 1 µm in vertical. The natural beam stability is within specifications (see table 1) in horizontal but needs to be improved by a factor of two in vertical. The main contribution to the vertical beam noise is at 50 Hz, the frequency of the mains. The lines at 46 Hz and 54 Hz correspond to the first eigen modes of the girders.

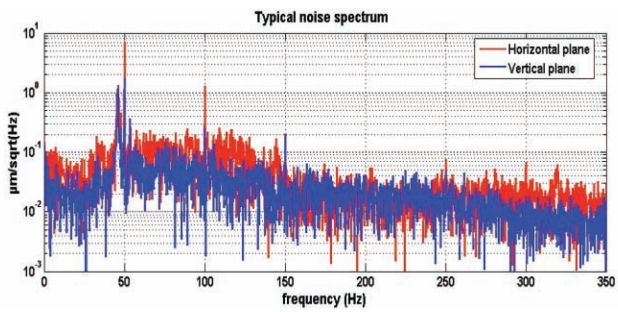

Figure 1: Natural beam spectrum without feedback. Most of the beam noise is below 150 Hz.

The beam movements during crane operation or gap changes can reach up to 10 μm in vertical and need to be damped in both H and V planes. The slow drifts, after machine warm-up, are in the 20 μm range over an 8 hour shift.

DATA DISTRIBUTION

In order to have a global system, the position data from each BPM module has to be distributed to all the points where the processing is done. As the processing is distributed in the BPM FPGAs, we have implemented a communication system between them. This is done with a dedicated network, linking all BPM modules together. Two different kinds of link are used:

- Copper cables links are used for the small length connections inside each cell, (Fig. 2).
- Multimode optics fiber links are used for 30 meter connections between cells, (Fig 2 and 3).

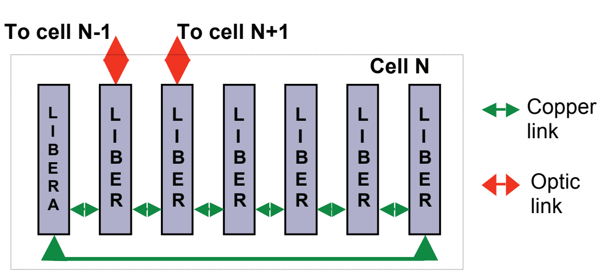

Figure 2: Topology of the dedicated network. In one cell, LIBERA modules are connected with a 'ring' topology with copper links. Two modules per cell are connected to neighbour cells with optic fibers.

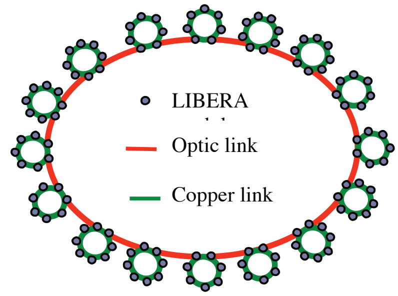

Figure 3: Topology of the dedicated network.

Data distribution all over the ring is controlled by a Communication Controller (CC) implemented in the FPGA of every BPM module. This CC has been designed by Diamond Light Source [4]. At the beginning of each time frame, the CC reads the data provided by its own BPM, and sends it over the network to its neighbours. Then, new incoming data from other BPMs are stored and forwarded to all the neighbours. In order to avoid network overflow, incoming data that is received for a second time is simply discarded. The main advantage of this protocol is that it fits any kind of topology for the dedicated network. The topology needs to be optimised for minimizing the number of BPMs a frame has to go through. With the present SOLEIL topology the data distribution process takes about 25 µs. The time-out for data distribution is configured to 60 µs in order to keep some margin in case of link failures.

DATA PROCESSING

FPGA Implementation

The FOFB algorithm has been fully integrated in the BPM modules FPGAs. On top of the processing for position measurement (provided by Instrumentation Technologies), we added our own Fast Feedback application. The coding has been done in VHDL (*Very high speed integrated circuit Hardware Description Language*) and simulated, before its integration into the FPGA. The application can be split into 5 main blocks (Fig. 4):

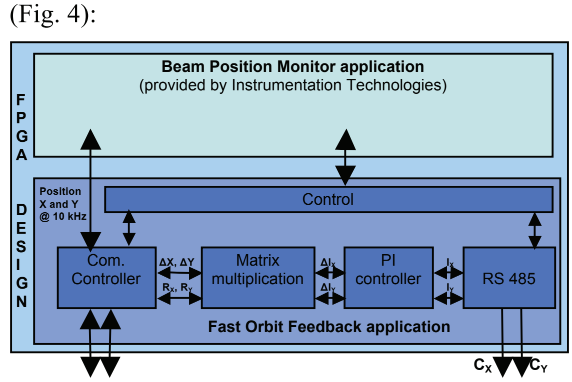

Figure 4: FPGA implementation.

• Communication Controller: This block allows the data distribution between BPM modules (see previous paragraph).

• Matrix Multiplication: To compute the correction this block has to perform 120 multiplications and additions for each plane. In order to save FPGA resources, multiplications are done serially, and one plane is computed after the other.

• PI Controller: In order to adjust the gain and the uncorrected error of the loop, we need a controller. The proportional part is applied offline when configuring the system, by multiplying the inversed response matrix by the appropriate coefficient. The integrative part is implemented in the FPGA as a simple integrator with an adjustable coefficient (Eq. 1).

$$I_N = \Delta I_N + coeff * I_{N-1} \quad (1)$$

With:

I_N : The next corrector setting

ΔI_N: The matrix multiplication result

coeff: The integrative coefficient

I_{N-1}: The previous corrector setting

• RS 485: This block shapes and serializes the correction set-points before sending them to the power-supplies on a RS 485 link. The communication over this link is only one way, from BPM module to power-supply. Each frame is 22 bits long: 16 bits for data, 2 for parity and 4 for synchronization (Fig. 5). The transmission rate is 1.25 Mbits/s and the transmission delay is around 20 µs.

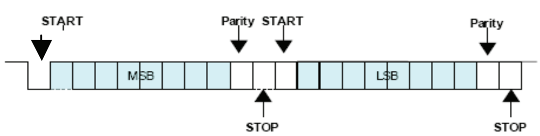

Figure 5: Communication protocol over the RS 485 link.

• Control: This block allows the control and the monitoring of the Fast Feedback Application. Each BPM module sends to the control system some statistics on the computed correction values for both planes (average, minimum, maximum). Those data are refreshed at 10 Hz.

Latency

The main part of the system latency is caused by the processing of the position data (BPM functionality). Time allowed for data distribution could be reduced by increasing the redundancy in the dedicated network (Table 2).

Position processing	190 µs
Data Distribution	60 µs
Matrix Multiplication	5 µs
PI Controller	1 µs
Serialization and transmission to Power Supply	20 µs
Total of FPGA delays	**~280 µs**
Power supply latency	20 µs
Eddy current in vacuum chamber	~60 µs
Total of delays	**~360 µs**

Table 2: Decomposition of the system latency

OPEN LOOP MEASURMENTS

Two series of open loop measurements have been performed.

Before implementing the algorithm, the whole electronics response was measured, from the power supply to the LIBERA outputs, thus including corrector, vacuum chamber transmission and beam response. This was done by applying a sweeping frequency signal on the power supply input and recording the resulting motion measured on the LIBERA output. The measured 3dB bandwidth is higher than 2 kHz in both planes (Fig. 6).

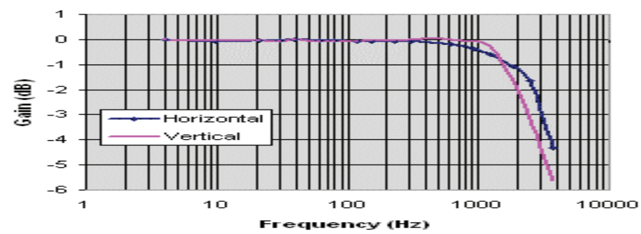

Figure 6: Bandwidth of the power supply + corrector + vacuum chamber + beam, measured on a BPM.

A second series of open loop measurements was performed during the commissioning with the whole open loop, including the computing delays in the FPGA. This was done by using an Agilent 35670A signal analyser equipped with two PR30A current probes, allowing to get amplitude as well as phase response. The 35670A source sweeping frequency signal was connected to the input of a voltage driven power supply;and the power supply output to the air-corrector. The corrector current was measured with a PR30A probe connected to the 35670A first input; meanwhile, the matrix output measured by the second probe was connected to the second input.

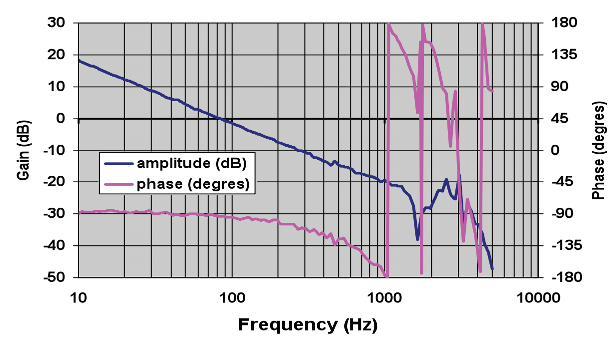

Figure 7: Open Loop Frequency Response (Horizontal plane with accumulator; 48x48 matrix 48 eigen values; gain=25).

The loop stability and the expected closed loop performance were deduced from these measurements and could be compared with the experimental behaviour of the feedback, and were found to be in good agreement (Fig. 7,8).

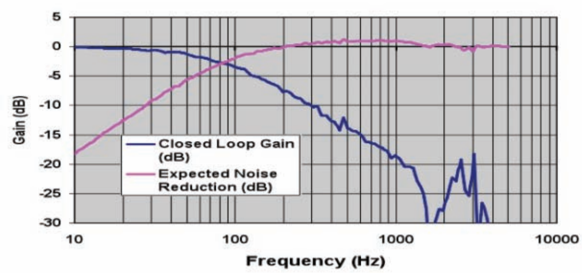

Figure 8: Expected Closed Loop Frequency Response (Horizontal plane with accumulator; 48x48 matrix 48 eigen values; gain=25).

COMMISSIONING

First tests of the SOLEIL Fast Orbit Feedback were started in December 2007 and are still currently in progress. The modularity of the system makes quite easy any change in configuration, allowing quick changes in gain, PI Controller coefficients, as well as the numbers of correctors, BPMs and matrix eigen values involved in the feedback loop. Up to now, ten 8-hour Machine shifts have been dedicated to these tests, allowing to solve a few bugs and to address several issues.

Bugs and issues

Among the bugs, a very simple (once solved), but quite disconcerting one was due to division of signed numbers. Because of encoding, the rounding of the division was to the lower nearest integer for positive numbers but also for negative ones (instead of higher nearest integer in this case). This lead to a non-zero mean value noise, which gave rise to diverging values when using accumulator for integration.

The other main issue during these first tests was communication reliability of the network. In a previous version of the network, all the LIBERAs were ordered in a serial (single ring) network, resulting in poor redundancy and long communication delays in case of link failures. This lead to large spikes (several hundreds of µm) on the orbit any time a communication problem was occurring (up to every few minutes in the worst cases). The new network scheme now implemented reduced the whole communication delay by a factor 2 when no communication hitch occurs (from 50 to 25µs), and allows to work even with a permanent open link.

Test set-up

During these test shifts, only 2 configurations were tested: 48 and 120 BPMs, both using 48 correctors.

The loop gain was optimized experimentally, and the experimental behaviour was compared with the expected performance deduced from the open loop measurements.

Up to now, tests were performed without the SOFB running, assuming that the Fast Orbit Feedback should be able to correct even DC components (drifts or crane displacement or slow moving insertion gap induced beam movements). In order to measure these effects, several tests were performed: i) comparing long time (several hours) orbit records with and without feedback, while changing insertion gaps and moving the cranes ii) frequency spectrum analysis on BPMs, and on the few X-BPMs currently available on the dipole beamlines.

EXPERIMENTAL RESULTS

The FOFB reduces the high frequency noise (1 to 100 Hz) within the σ/10 goal for all source points, especially in the case of the hard X-ray beamlines in the vertical plane (fig. 10). There is a strong positive effect up to 50 Hz, but with some noise addition above 100 Hz. Integrated noise is suppress by nearly a factor of two in the band 1-350 Hz.

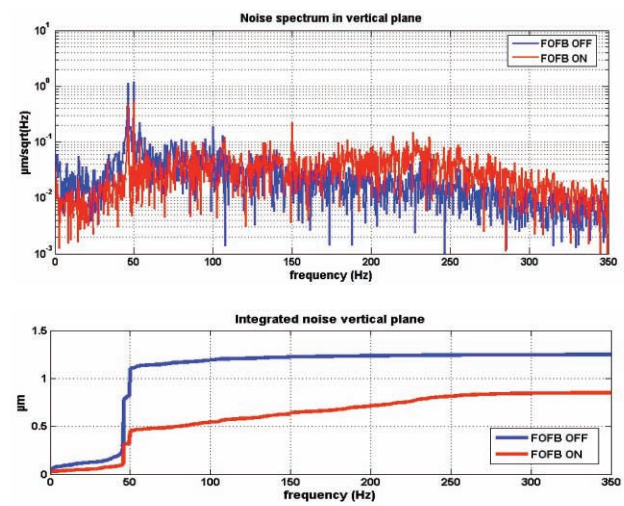

Figure 9: Vertical beam noise with and without feedback (external sensor).

In order to measure the effects in the 0.01-1Hz BW we have repeated 4 times the same transitions in gap and phase of some insertion devices with 4 configurations: no Orbit Feedback, SOFB ON, FOFB ON with 48 BPMs and FOFB ON with 120 BPMs.

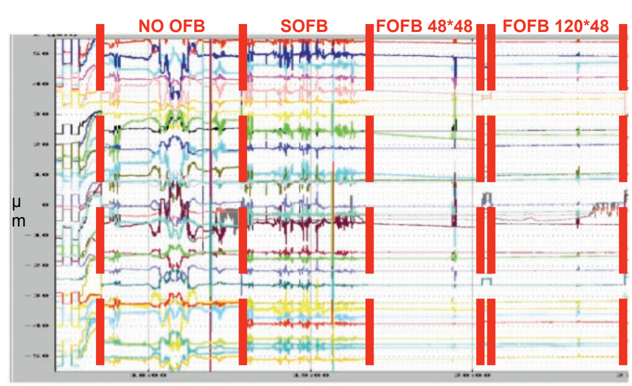

Figure 10: Good suppression of beam position perturbations during gap changes(0.01 Hz-1 Hz BW).

From table 3, the optimum configuration is 120 BPM x 48 correctors in the vertical plane in order to have an action on the bending magnet source points, but this is not an issue in the horizontal plane, and the 48 BPM x 48 corrector is better. The air-corrector strength after a few hours of operation remains relatively small which gives confidence for operation up to an 8-hour shift, between two injections.

Photon Source		ΔX µm	ΔX angle µrad	ΔZ µm	ΔZ angle µrad
Bending Magnet ≤ 35 keV	σ/10	N/A	N/A	1.5	5.3
	no FOFB 3.5h	4.5	11	17	1.6
	48x48 for 2h	1.5	0.9	4.1	0.6
	120x48for3h	0.2	0	0.3	0.1
Hard X-ray IDs	σ/10	39	1.5	0.55	0.52
	no FOFB 3.5h	15	1.5	3.2	1.6
	48x48 for 2h	0	0	0	0
	120x48for3h	0.3	0	0.3	0.1
Soft X-ray IDs	σ/10	18	3.4	0.65	1.6
	no FOFB 3.5h	10	2.5	5.8	1.6
	48x48 for 2h	0	0	0	0
	120x48for3h	0.5	0.1	0.5	0.1
UV ID	σ/10	32	4.6	6	4.2
	no FOFB 3.5h	12	0.5	4	0.3
	48x48 for 2h	0	0	0	0
	120x48for3h	0	0.1	0.6	0

Table 3: few-hour stability with FOFB, from DC to 0.01 Hz (slow drifts).

Some optimization is currently under progress on the number of eigen values selected for the SVD inversion. This leads to even more promising results (suppression by a factor of 3 of the integrated vertical noise in the 1-350 BW)

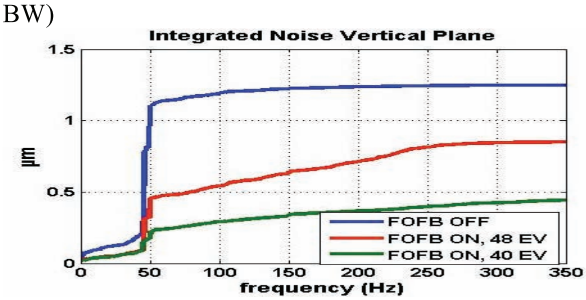

Figure 11: Optimization on the number of eigen values.

COMPATIBILITY WITH SOFB

As said previously, we have a different set of correctors for the Slow and the Fast Orbit Feedback systems. The Slow Orbit Feedback operates from DC to 0.05 Hz (limited by the latency of its power-supplies). At the moment, the Fast one is operating from DC to 100 Hz. With different correctors and a common operating frequency band, the 2 system will not be compatible.

Two options are still considered:

- The first option is to separate the operating frequency bands of each system. In this case, the FOFB 'area' will have to start at 0.1 Hz instead of DC. It has the main advantage to keep the two systems completely independent. But it will also create a frequency dead-band (from 0.05 Hz to 0.1 Hz) where beam movement will not be corrected at all (Fig. 11 a).
- The second option is to keep the Fast Orbit Feedback system working from DC. In this case, the Slow Feedback system will have to read the DC part of the current in the fast corrector and integrate it before applying its correction. The Slow System correction rate could be decrease as its main role would be mainly to relieve the fast power-supplies and correct the RF frequency. The two systems are no more independent and a reliable communication has to be implemented between them. The main advantage of this solution is to have a continuous frequency band where the beam movement can be suppressed (Fig. 11 b).

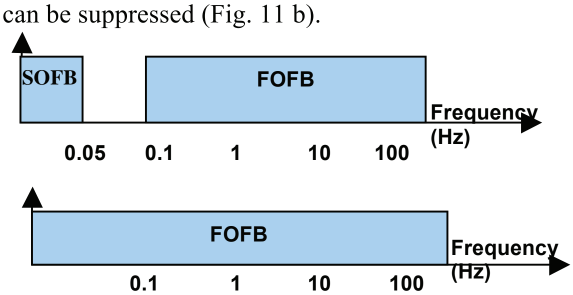

Figure 12: Two options: a) 2 independent systems with a dead-band, b) FOFB correcting from DC.

CONCLUSION

The Slow Orbit Feedback suppresses efficiently the slow drifts due to thermal effects, but has no significant effect on beam movements and vibrations faster than 0.05 Hz. The Fast Orbit Feedback corrects efficiently the latter and seems able to correct well enough the slow drifts. The initial idea of having the two feedback systems working simultaneously but separated in the frequency domain by a dead band may not work properly for suppressing the perturbations caused by the cranes and by the undulator gap changes. The perturbation spectrum is likely to cover the dead band and would not be suppressed. We are investigating the possibility of using the FOFB with an occasional relief of its DC correction by the Slow System.

The Fast Orbit Feedback system gives very promising results and is expected to be available for user operation in the coming months.

ACKNOWLEDGEMENTS

We thank I. Uzun and G. Rehm from Diamond Light Source and E. Plouviez from ESRF for their collaboration. We are also grateful to the Instrumentation Technology staff involved in the LIBERA project.

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